

**NASA
Technical
Paper
2558**

February 1986

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Space Powerplants Using
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(NASA-TP-2558) TECHNOLOGY FOR BRAYTON-CYCLE
POWERPLANTS USING SOLAR AND NUCLEAR ENERGY
(NASA) 15 p HC A02/MF A01 CSCL 10B

N86-21577

Unclass

H1/20 04127

NASA



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Technology for Brayton-Cycle
Space Powerplants Using
Solar and Nuclear Energy

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Scientific and Technical
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Summary

Brayton-cycle gas turbines have the potential to use either solar heat or nuclear reactors to generate from tens of kilowatts to tens of megawatts of power in space, all this from a single technology for the power-generating system. Their development for solar-energy dynamic power generation for the space station could be the first step in an evolution of such powerplants for a very wide range of applications. At the low power level of only 10 kWe, a power-generating system has already demonstrated overall efficiency of 0.29 and operated for 38 000 hr. Tests of improved components show that, if installed in the power-generating system, these components would raise that efficiency to 0.32; this efficiency is twice that so far demonstrated by any alternate concept, a characteristic especially important for solar power systems. Because of this high efficiency, solar-heat Brayton-cycle power generators offer the potential to increase power per unit of solar-collector area to levels exceeding four times that from photovoltaic powerplants based on present technology for silicon solar cells.

For the heat source, paraboloidal mirrors have been assembled from sectors here on Earth. One mirror, 1.5-m diameter, had a standard error for its surface of only 1 arc-min and a specific mass of only 1.3 kg/m². A heavier mirror (nearly 5 kg/m²), assembled from 12 sectors, had a standard surface error of 3 arc-min but was 6 m in diameter. Either of these mirrors is sufficiently accurate for use with the Brayton cycle, but the techniques for actually assembling large mirrors in space must yet be worked out. For use during the shadow period of a low Earth orbit (LEO), heat could be stored in LiF, a salt that melts at 1121 K (1558 °F) and whose latent heat of fusion exceeds 1 MJ/kg. Because of the prior experience with its fabrication and of its tolerance of the thermal cycling in LEO, Nb-1Zr was selected to contain the LiF, and its feasibility was demonstrated by 5000 hr of thermal cycling between 1090 and 1310 K (1500 to 1900 °F). Based on this technology, a receiver was designed and built of Nb-1Zr, LiF being the heat-storage medium. Tests of three receiver tubes for 2000 hr (1250 Earth orbits) also confirmed the receiver's thermal performance. The receiver outlet temperature was 1075 K (1475 °F) or greater throughout the test.

This technology for solar Brayton-cycle power generation is also directly applicable to Brayton cycles using nuclear reactors as their heat sources. For higher temperatures, a family of tantalum alloys was evolved, ASTAR-811C (Ta-8W-1Re-0.7Hf-0.025C) being the most fully explored.

For this alloy, over 300 000 hr of creep testing spanned the temperature range of 1140 to 1920 K (1600 to 3000 °F). Correlation of these data shows that Brayton-cycle powerplants are suitable for long-term service in space at temperatures up to 1500 K (2240 °F). This same technology for Brayton space power systems could then be readily extended to generate 10 to 100 MW in space by exploiting existing technology for terrestrial gas turbines in the fields of both aircraft propulsion and stationary power generation. Thus, this single concept for power generation has the potential to evolve in modest increments from tens of kilowatts for the space station to hundreds of megawatts for military applications in space.

Introduction

Prologue

As one engaged for over 25 years in long-range research on power generation in space, I ponder what conditions we power technologists must meet in order for our advanced concepts and their promise to be exploited in space. My overall goal in this report is to examine this question and, from that examination, to suggest a path for both rapid and economical evolution of our capabilities to produce power in space.

NASA's plans for a space station present us technologists with not only a new, larger demand for power than we have had before but also with a new opportunity to evolve advanced power concepts with lower risk than we have previously faced. One of my purposes is to consider the manner in which advancing power technology can not only permit the space station to become a better space station but also how that advanced technology, despite its risks, might reduce the overall risks in development and operation of the station itself.

Once the space station is being used effectively in space, the interaction between the space station and its electric powerplant will provide a mutually beneficial, synergistic environment in which the benefits of advancing power technology can be realized with low risk and at low cost. In part, I will examine the path that might permit this.

But the space station is not NASA's final mission in space. To some degree, we must also look beyond the station's effective exploitation for utilitarian purposes to the capacity it will give us for expanding our capabilities in space. For example, a permanently inhabited astronomical observatory on the lunar surface is currently beyond our capacity, in any practical sense. For such a laboratory, a truly enabling

technology is a nuclear powerplant. Thus, as we evaluate the potential merits of alternate approaches to power generation for the space station, we ought to also weigh the benefits that such enabling technology would yield for future missions, such as to a scientific laboratory on the lunar surface. In part, one of the justifications for the station itself should be that it provides the capability for advancing this technology at low cost and with low risk. So I will discuss how the station might permit us to achieve this and other advances with low cost and low risk.

But the keystone in this whole endeavor is the space station itself. So our discussion of power technology must begin with power for the station. As a precursor of even that discussion, we power technologists must doff our regalia as power technologists, don the raiment of the mission manager, and contemplate our technologies from her perspective.

Evolution versus Revolution

Let's consider this question: How does a new type of power system come into use in space? Apart from technological creations for the sake of technology alone, new classes of a power system are driven by mission requirements. Although technologists are struck by the glitter of new technology, that gloss has little effect on mission selection of a concept for generating power in space.

Even as beauty lies in the eye of the beholder, mission suitability resides in the mind of the mission manager. In choosing her mission, this manager draws on technology known to her and especially on those technologies that she and her associates have already used successfully. Missions requiring a new approach to power generation are generally rejected as too risky. A truly enabling technology is thus rarely even considered.

A power-system technologist thus confronts a dilemma: His new concept for power generation will be rejected by each mission manager until his concept has actually been used successfully by this or another mission manager. This chain of circumstance thus places in a dominating position those concepts for power generation that are only modest evolutions from what has already performed successfully in space. To the degree that a concept is a revolution in power generation, it carries a prohibitive burden of risk and uncertainty in the mind of the mission manager.

In contrast with this, concepts for power generation that can *evolve* in a succession of modest steps can achieve substantial progress over a period of time at low cost and with low risk. Such evolutionary progress is accepted, even welcomed, by the mission managers.

Solar Power for the Space Station

Environment aboard the station.—The space station provides a revolutionary opportunity for new concepts in power generation. First, the planned power levels of 75 to 300 kWe are themselves a revolution, so much so that the

balance of merits of alternative concepts requires reexamination. At these power levels so far above the range of our experience in space, the interference of the power system with both the space station and its operations may require a new class of power generator. But more of that later.

Second, the station itself will evolve, a second revolution in space missions. The power it requires will initially be at the low end of this range, perhaps 75 kWe, and the power demand will grow over about 10 years to perhaps 300 kWe. Successive additions of power modules will gradually increase the station's power capacity in order to meet the rising demand for power. In turn, these power modules themselves might successively evolve in performance.

Third, aboard the space station advanced concepts for power generation can be exploited with lower risk than would be encountered on other space missions, a third revolutionary aspect of the station. Inasmuch as the station's complete powerplant will be modular, failure of a given power module would result in only partial loss in the station's capability. Even as successive visits to the station permit growth in power by adding power modules, they also provide the capacity to replace defective, damaged, or worn-out power modules. Thus, the station's operational features markedly reduce the risk from using advanced concepts for power generation.

A strategy for phased introduction of advanced power concepts aboard the station can also reduce the risk from introducing the advances. Consider, for example, that the initial space station is equipped with arrays of photovoltaic solar cells but that these arrays would be a problem for the station at the very highest powers because of their large area. The area handicap could be overcome if the arrays of solar cells were replaced in service by more-compact, advanced power modules. If the arrays of solar cells have the capability for both deployment and retraction, the arrays being replaced could be retracted and stored rather than discarded. In that case, the arrays of solar cells would still be available for use if problems were to arise with the advanced power modules, risk from the new concepts thereby being substantially diminished.

Area is a problem.—For the photovoltaic arrays, plane panels having silicon as the semiconducting material for the cells themselves represent the technology on which our principal experience in power generation is based. For supplying power during the time the spacecraft is in the Earth's shadow, nickel-cadmium batteries are usually charged during the sunlit portion of the orbit and discharged in darkness. Hydrogen-oxygen fuel cells have also seen substantial service, chiefly during flights of inhabited spacecraft in the Gemini and Apollo missions. Recent extensions of that fuel-cell technology make regenerable fuel cells a likely candidate to replace the nickel-cadmium batteries for energy storage in combination with arrays of photovoltaic cells. The overlapping uses of water, hydrogen, and oxygen for life support, propulsion, and power generation may be significant advantages of the regenerable fuel cells.

For those combinations of silicon photovoltaic cells plus either rechargeable batteries or regenerable fuel cells, the powerplant's orbit-average, steady output is about 42 W/m^2 , if we include (1) the degradation in array output over a period of time, (2) the efficiency with which storage batteries or regenerable fuel cells can be charged and discharged, (3) the losses in conditioning power from the solar arrays, and (4) the time fraction (as high as 38 percent) in the Earth's shadow. In turn, a 300-kWe powerplant would require about 7100 m^2 (or roughly 1.8 acres) of such arrays.

Panel areas such as that pose several problems for the space station. Inasmuch as these very large panels must extend from the station and be oriented toward the Sun, they may obscure the view from the station and might also interfere with the orbiter's rendezvous with the station. Although atmospheric drag on the arrays requires periodic propulsion for orbit maintenance, the annual consumption of propellant is modest for the 500-km orbit altitude commonly considered for the station.

On the other hand, atmospheric drag is a critical factor affecting the length of time the station would remain in orbit in the complete absence of propulsion. Although the conditions for a 90-day orbit-decay period are frequently cited for the station, this time seems to me to be too short. Consider, for example, the impact of a major problem with the shuttle that might interrupt scheduled flights to the station for, say, a year. Even in that unlikely event, the space station should remain in orbit. For us to achieve that, a substantial reduction in atmospheric drag and thus in area for solar collection is required.

Photovoltaic cells made of GaAs rather than silicon offer some hope for reducing array area. Their steady, continuous power per unit area averages about 54 W/m^2 , a value reducing array area about 22 percent below that of silicon.

Overall risks for the space station. — Any change in concept for the power generator from the tried and true planar arrays of silicon solar cells imposes some increase in uncertainty concerning the power system itself. On the other hand, if the area for collecting solar energy could be reduced, the accompanying reduction in atmospheric drag of the power generator would reduce the risks in orbit maintenance of the space station and in shuttle operations. The current 500-km (270-n-mi) orbit altitude of the station was chosen, in part, to reduce this atmospheric drag, but that stretches the shuttle's propulsive capability and requires direct insertion. Decreasing orbit altitude of the station by, say, 90 km (50 n mi) would increase the shuttle's payload mass (ref. 1), additional benefits being increased margin in shuttle performance and more frequent and economical shuttle operations through opening up the window of launch opportunity.

Thus, acceptance of some technological uncertainties in power generation might reduce the risk in the entire program for the space station. For the power program, a valuable goal is to substantially raise power density (W/m^2) for a solar power system with only moderate risk. One purpose of this

paper is to examine the technology for Brayton-cycle solar-thermal powerplants and from that technology to infer the increase in power per unit solar-collector area that is reasonably achievable.

Future Demands for Advanced Power Concepts

When considering future demands for advanced concepts to generate power in space, we power technologists generally set down a wishlist of such demands. Carried out in this way, such an assessment is, of course, self-serving. The risks in developing an advanced powerplant, as viewed by a mission manager, are sublimated by the technologist in setting loftier goals to advance technology.

The process of delineating the path to new, advanced concepts for power generation should be inverted. As previously summarized, we power technologists must don the mission manager's raiment and assess the future demands for power from her point of view. In that case, risk and cost of a new development become very important issues, and mere technological sparkle loses its sheen. If a modest evolution of a current, conventional concept will permit the mission to be carried out even with performance penalties, the current concept will nearly always be chosen over the advanced. If not, the mission will usually be redefined to match what is readily achievable by only modest improvement of a current concept.

Only rarely will the advanced concept be selected, and the cost and risk of the new development will be crucial factors affecting that choice. We power technologists should therefore reevaluate our research programs as well as our advocacy of power concepts in the light of these facts. This paper is a first attempt to do just that.

Given that caveat, let us examine a few of the likely future demands for power beyond solar-dynamic power generation for the space station. To a substantial degree, I will emphasize risk and cost in that assessment.

A nuclear powerplant to generate hundreds of kilowatts could, in principle, be more compact than any comparable solar powerplant in Earth orbit. By its very nature, such a nuclear powerplant would generate its electric power from heat supplied by a nuclear reactor. If solar-thermal powerplants were used by the space station instead of photovoltaic arrays, a low-risk and low-cost evolution of that solar-thermal concept would replace the paraboloidal mirror and solar-heat receiver by a nuclear reactor, peak cycle temperature being kept constant.

For later, advanced versions of such a nuclear powerplant, performance could be further enhanced by substituting improved materials and higher operating temperatures; reference 2 shows part of the extensive data base on a family of tantalum alloys and justifies the use of a member of that family at temperatures up to 1500 K (2240°F), based on over 700 000 hr (or 80 yr) of high-temperature creep testing. With only modest risk, these refractory alloys could replace in later

power modules the lower-temperature materials already in service, powerplant design being basically unchanged except for that. For margin, initial use temperature could be, say, 1200 K (1700 °F) rather than the 1500 K potential, the 300 K difference being the margin to reduce risk when introducing a new material. Following a period of successful testing on Earth and of actual service in space, the operating temperature of follow-on power modules could be gradually increased to the 1500 K potential defined by the available technology.

Thus, I envision the following sequence of powerplant types and total installed powers for this evolutionary, low-risk, low-cost approach: (1) solar-thermal power for 75 to 300 kWe, (2) nuclear-thermal power using the same power-generating system design and the same peak cycle temperature for 200 to 500 kWe, and (3) high-temperature nuclear-thermal power for 300 to 1000 kWe. These nuclear powerplants would not only be appropriate for service aboard the space station but also for powering large communication satellites, for powering a lunar-based astronomical observatory, and for electrically propelling spacecraft in exploring the solar system.

The Department of Defense has also expressed some interest in powerplants of very high power capacity, perhaps 10 to 100 MWe, for the Strategic Defense Initiative (SDI). For those high powers, the supporting research program currently focuses on delineating the concepts and the technologies that would provide maximum (optimum is the common term) performance in that application. In line with my earlier strategy for the power program, one might ask if the technology for the 1000-kWe powerplant just mentioned is directly extendable by an evolutionary approach to these very high powers even though it might not provide the maximum performance at this power level. If so, a few billion dollars might be saved by not developing a completely new concept, a saving so large that some compromise in performance is not only acceptable but very worthwhile.

Specific Purposes

In a program on technology and development of advanced concepts for generating power in space, it is important to choose a path that will lead to selection and actual use of the concepts by the mission managers. Crucial in this selection and use is reduction in risk as a result of only a gradual evolution of the power systems. In pursuit of these goals, a single genus of power generating system (closed Brayton-cycle gas turbine) will be explored for its potential (as indicated by current technology) for use in all of the following successive applications:

(1) Generate powers from 75 to 300 kWe aboard the space station using solar heat. Crucial in this role is a substantial increase in power output per unit of collector area in comparison with planar arrays of silicon solar cells.

(2) Aboard the space station, generate power from 200 to 500 kWe from nuclear-reactor heat, peak cycle temperature being the same as for generating power from solar heat in item (1).

(3) Through the substitution of known materials in item (2), gradually raise peak cycle temperature (an evolution) to 1500 K. Aboard the space station, generate 300 to 1000 kWe.

(4) Explore the potential for direct application of the technology in item (3) for generating 10 to 100 MWe of electric power in space.

Solar Brayton-Cycle Power for Space Station

Solar Mirrors

Figure 1 shows a paraboloidal mirror 6 m (20 ft) in diameter and weighing nearly 5 kg/m². The 12 sectors of this magnesium mirror were shaped by creep-forming over a heated aluminum mandrel that had been machined to the appropriate contour. In assembly by hand, the sectors were joined by bolting flanges along their margins. The mirror was given a glossy and highly reflective surface in the following way: After spray-coating and curing a liquid polymer film, the mirror's front surface was coated with evaporated aluminum and SiO (ref. 3). Measured specular reflectivity was 0.88. The orientations of small elements of the mirror surface were measured by optical inspection (fig. 2) at 32 400 points,



Figure 1.—Paraboloidal mirror 6 m in diameter.

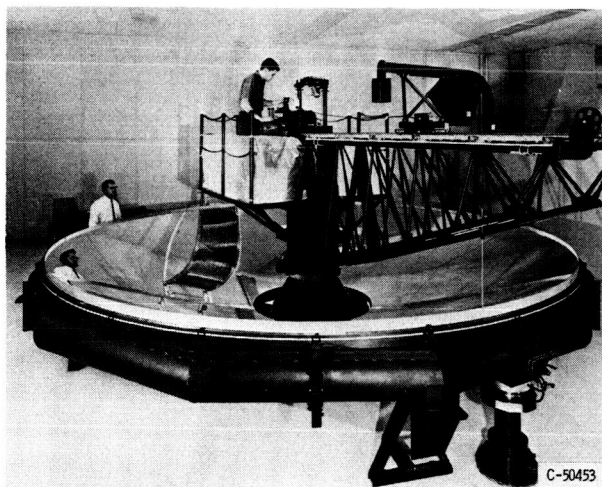


Figure 2.—Optical device for inspecting paraboloidal mirrors.

the errors having a Gaussian distribution with a standard error of 3 arc-min.

A second mirror 1.52 m (5 ft) in diameter and weighing 1.3 kg/m^2 consisted of aluminum sectors $400 \mu\text{m}$ thick stretch-formed over a paraboloidal mandrel (ref. 4). Following assembly of the sectors, optical inspection showed the standard error of the mirror surface to be 1 arc-min. The techniques for assembling such mirrors in space have yet to be evolved.

Such a mirror would focus the collected solar energy onto an aperture in a heat receiver. The Sun's image produced by the mirror is somewhat increased in size by the errors in the mirror's surface, and this requires increasing the aperture's size over that for a perfect mirror. Heat is radiated from the receiver's internal cavity through this aperture, more heat being radiated from a high-temperature receiver than from a low and more heat from a large aperture than from a small one.

Although solar energy can be collected only during the sunlit portion of the orbit, heat is, of course, radiated from the aperture for the entire orbit. A door could cover the aperture and thereby reduce heat loss during the time in the Earth's shadow, but that possible gain in performance is neglected herein.

The thermal performance of such a mirror-receiver combination is analyzed in reference 5 and summarized in figure 3, aperture size being the optimum in each instance. For a 96-min orbit, 60 min are considered sunlit. Mirror reflectivity is herein conservatively taken as 0.85, and 10 percent of the incident solar beam is assumed to be obstructed; these assumptions reduce even the ideal efficiency of solar collection to 0.765. This efficiency is further reduced if the mirror's standard error is large and the receiver-cavity temperature high. For the mirror standard errors of 1 to 3 arc-min (0.29 to 0.87 mrad) already demonstrated, attainable performance is very close to this ideal; for receiver temperatures up to 1100 K, collection efficiency is 0.75 or greater.

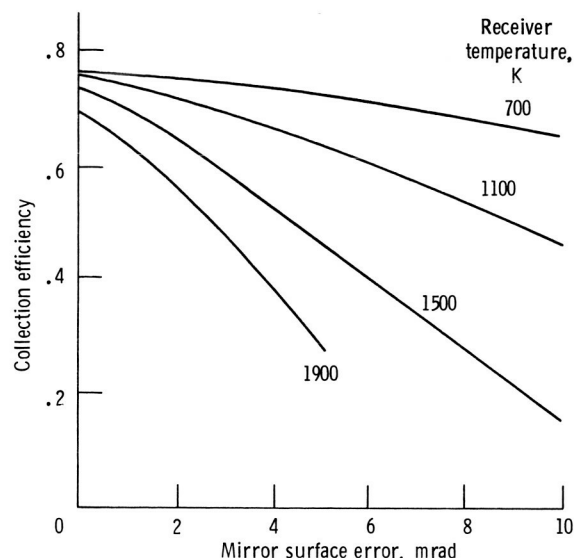


Figure 3.—Effects of mirror error and receiver temperature on collection efficiency. Reflectivity, 0.85; sunlight obstruction, 0.10; 1 mrad=3.4 arc-min.

Durability of the mirror coating is crucial. For investigation of this question, two test specimens were flown on SERT II (ref. 6). The mirror surface consisted of 190 nm of aluminum and an overcoat of SiO. At the orbit altitude of 1000 km, these specimens faced the Sun for 44 months without change in their reflectivity.

Heat Receivers

Phase change of a salt is an effective means of storing solar heat during the orbit's sunlit portion for use during the shadow period, both heat of fusion and melting temperature of the salt being important variables. Candidate materials are listed in table I (ref. 7), LiF being outstanding for its high heat of fusion for temperatures in the range of 1100 K (1500 °F).

A solar heat receiver generally experiences a thermal transient of heating in sunlight and cooling in shadow. In turn, thermal fatigue is a potential problem. For a given imbalance in heat input within the receiver, the cyclic thermal stress in the receiver depends on the thermal conductivity k of the metal of which it is built, on its thermal coefficient of expansion α , and on its elastic modulus E . Ability to tolerate this cyclic stress is measured by the stress S to produce 1-percent creep. The parameter $E\alpha/Sk$ is thus of interest.

Two candidate materials are compared on this basis in table II, Nb-1Zr having an advantage of 40 to 1 over L-605 (tradename, Haynes 25).

The chemical compatibility of three niobium alloys with LiF was explored in reference 8. Of these niobium alloys, Nb-1Zr has the most extensive history of use, but FS-85 (Nb-28Ta-10.5W-0.9Zr) and SCb-291 (Nb-10Ta-10W), being more highly alloyed, are stronger. Tubular capsules of these alloys were loaded with LiF and subjected to 3125 thermal

TABLE I. — CHARACTERISTICS OF HEAT-STORAGE MATERIALS (REF. 7)

[Composition of mixtures, where given, are in weight percent.]

Material	Melting temperature, K	Heat of fusion, J/g
KF	1125	454
Na ₂ CO ₃	1125	279
Ca	1123	221
LiF	1121	1044
LiBO ₂	1108	698
75NaF + 25MgF ₂	1105	649
62.5NaF + 22.5MgF ₂ + 15KF	1082	607
NaCl	1074	484
CaI	1057	142
CaCl ₂	1046	256
KCl	1043	372
67LiF + 33MgF ₂	1019	947
^a 65NaF + 23CaF ₂ + 12MgF ₂	1018	574
Na ₂ B ₄ O ₇	1013	523
Li ₂ CO ₃	998	605
MgCl ₂	988	454
60KF + 40NaF	983	479
LiH	956	2582
Al	933	388
60LiF + 40NaF	925	816
Mg	923	372
46LiF + 44NaF + 10MgF ₂	905	858
52LiF + 35NaF + 13CaF ₂	888	640
LiCl	883	470
52NaCl + 48NiCl	843	558
Ca(NO ₃) ₂	834	130
73LiCl + 27NaCl	825	430
48NaCl + 52CaCl ₂	773	328
49KF + 51LiF	765	461
80Li ₂ CO ₃ + 20K ₂ CO ₃	763	377
LiOH	743	930
11.5NaF + 42KF + 46.5LiF	727	442
80LiOH + 20LiF	700	1163
KOH	673	140
LiCl + KCl	623	255
KNO ₃	613	128

^aComposition corrected.

cycles between 1090 and 1310 K (1500 to 1900 °F), the 96-min cycles approximating conditions in a low orbit about the Earth. These 5000-hr tests found that all three alloys are compatible with LiF.

Based on these results, a receiver was designed (ref. 9) and built (fig. 4) of Nb-1Zr with LiF as the heat-storage material. Three tubes of that receiver were tested (ref. 10) under conditions simulating orbital operation for 2002 hr (1251 sunshade cycles). Outlet gas temperature cycled between 1073

TABLE II. — COMPARISON OF ALLOYS TO CONTAIN THE FUSIBLE MATERIAL

	Alloy	
	L-605	Nb-1Zr
Strength S for 1-percent creep in 1000 hr at 1200 K, MPa	16.5	60
Expansion coefficient, α , 1/K	17	8
Conductivity, k, W/cm-K	0.27	0.61
Elastic modulus, E, GPa	207	83
Parameter $E\alpha/Sk$	790	18

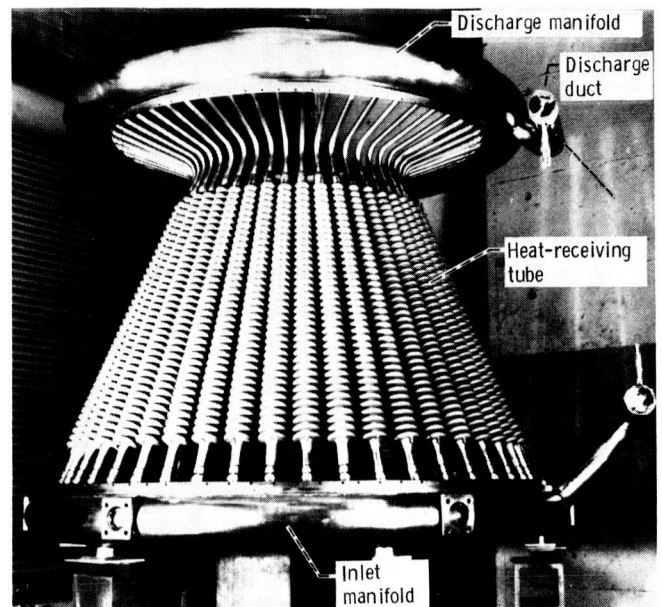


Figure 4. — Solar heat receiver of Nb-1Zr.

and 1117 K (1471 and 1550 °F). The highest temperature observed for the Nb-1Zr was 1183 K (1670 °F), well below the 1310 K (1900 °F) investigated in the compatibility tests. The complete receiver has not been tested in combination with a mirror focussing either actual or simulated sunlight.

Gas-Turbine Technology

A common size for turbomachinery components in gas-turbine research programs is illustrated by figure 5. This axial-flow compressor is 51 cm in diameter and driven by a 10-MW electric motor. A compressor (6-m diam) driving a wind tunnel is shown in figure 6, the mechanic in the photograph displaying the comparative size; 100 MW are required to drive this compressor. Gas turbines generating output powers of 10 to 100 MW are manufactured, sold, and operated every day for generating power here on Earth. Aircraft engines in regular service produce powers as low as a few hundred kilowatts but are generally of far higher power; for example, the kinetic energy imparted to the exhaust jet of a large aircraft engine during takeoff is of the order of 150 MW.

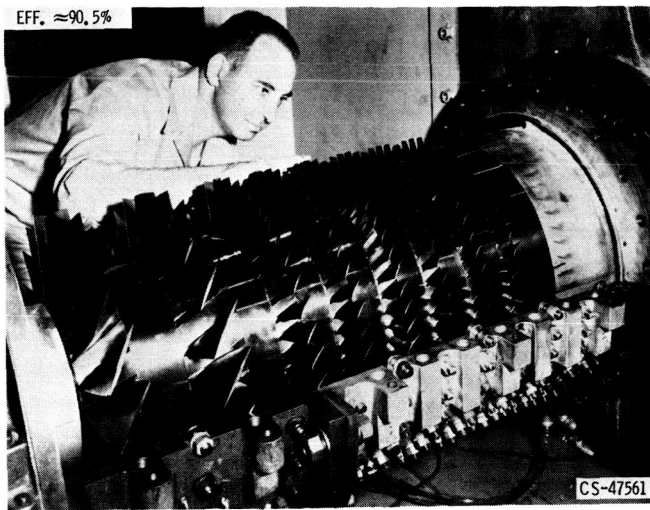


Figure 5. — Experimental compressor. Diameter, 50 cm; power consumption, 10 MW.

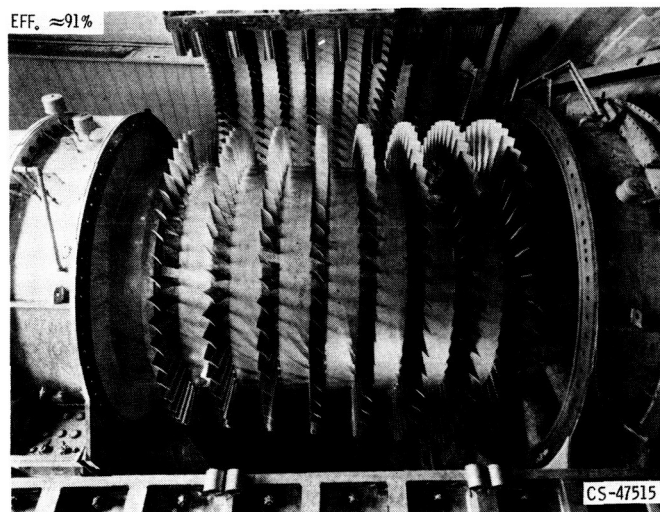


Figure 6. — Compressor for driving a wind tunnel. Diameter, 6 m; power, 100 MW.

In investigating power generation by gas turbines in space, a crucial technology issue was therefore to reduce power to much lower levels while still maintaining good efficiency. Small turbomachinery, as in figures 7 and 8, was investigated; figure 9 shows some of the performance data.

With these data as the basis, a gas-turbine powerplant was designed to generate 10 kW of power in space, which is of the general order of only 1 percent of the output of small aircraft gas-turbine engines. Despite this very low power output, high efficiency was a goal of the program. For long life, the rotor of the turbomachine was supported by gas bearings, the working gas being used as lubricant, as shown in the sketch in figure 10. The compressor, turbine, and synchronous alternator were mounted on a common shaft that turned 36 000 rpm. During operation, the rotor nowhere touched the stator, thereby entirely avoiding a possible wear mechanism. This Brayton rotating unit (fig. 11) was completely

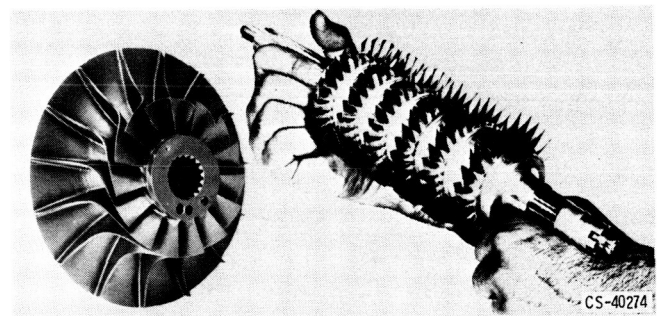
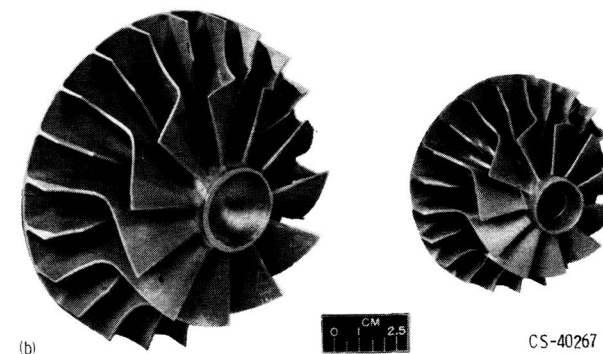
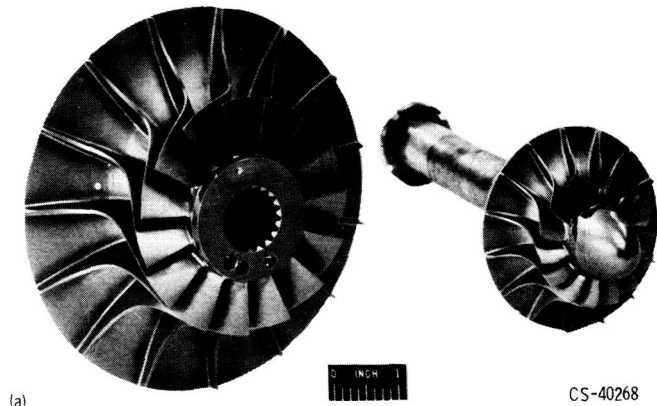


Figure 7. — Experimental compressors 152 and 89 mm in diameter.



(a) Compressors 152 and 81 mm in diameter.
(b) Turbines 152 and 81 mm in diameter.

Figure 8. — Small experimental turbomachinery.

stable in its performance for 38 000 hr, turbine inlet temperature being 1144 K (1600 °F) as described in reference 2.

The performance of this 10-kWe powerplant (complete but for the heat source) was measured in a large vacuum chamber (figs. 12 and 13). Measured efficiency was 0.29 at 10 kWe, based on net power output, all losses and parasitics being deducted. For example, the generated power was regulated by the powerplant in both voltage and frequency in spite of variation in either real or reactive electrical loads. Inasmuch as a motor-driven pump circulated coolant to a radiator for rejecting waste heat, the pump power was deducted. Because power from a battery would drive the alternator as a motor

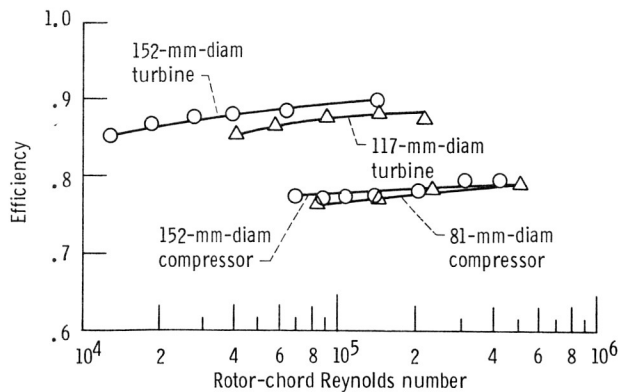


Figure 9.—Efficiencies of small turbomachinery. Turbine fluid, argon; compressor fluid, air.

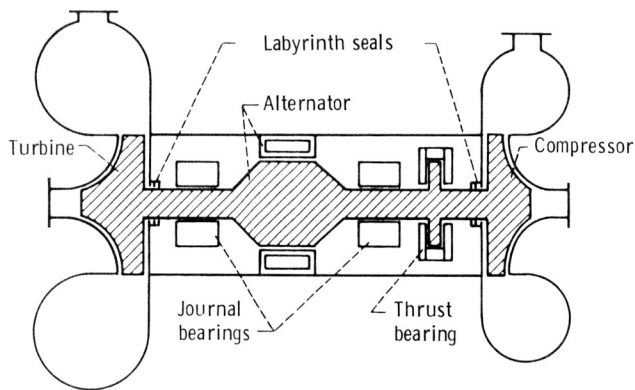


Figure 10.—Schematic of Brayton rotating unit.

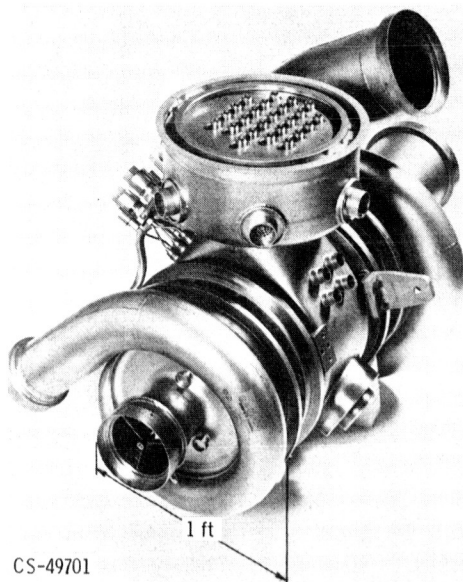


Figure 11.—10-kWe Brayton rotating unit.

for starting and restarting the powerplant, power to operate a battery charger was also deducted.

Tests of the individual components of the power-generating system revealed significant losses correctable by modification

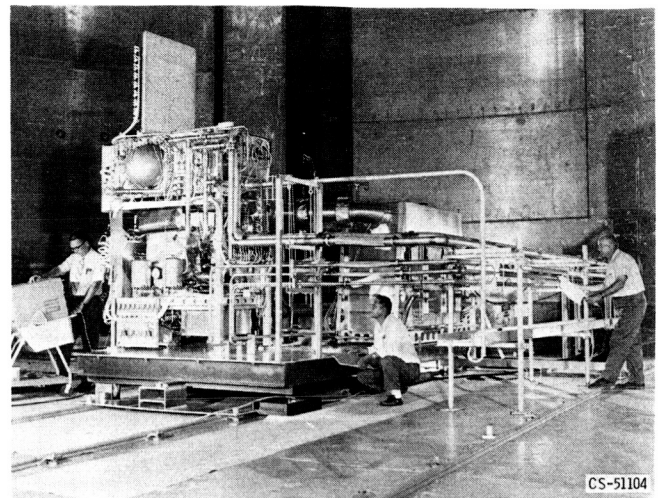


Figure 12.—Brayton power-generating system prior to test in Space Power Facility.

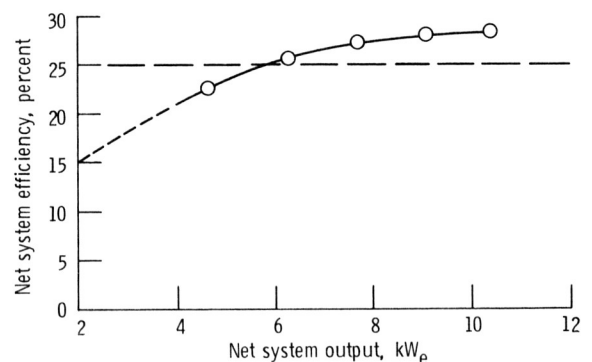


Figure 13.—Measured performance of Brayton power-generating system. Turbine inlet temperature, 1140 K (1600 °F); compressor inlet temperature, 300 K (80 °F).

or redesign. After such modification or redesign, component tests produced the following incremental improvements in performance: compressor efficiency, 0.03; turbine efficiency, 0.01; recuperator effectiveness, 0.01; and electrical components, 400 We. Had these improved and demonstrated components been incorporated into the power-generating system, overall efficiency would have risen from 0.29 to 0.32 (ref. 11). These efficiencies are considerably higher than those demonstrated by any other thermal powerplant for generating electric power in space (whether thermoelectric, thermionic, or the Rankine or Stirling cycles).

Solar Powerplants for Space Station

Let us now return to the performance goals we set down earlier, namely, assessing the amount of power that can be generated for each square meter of solar-collector frontal area. Solar intensity is taken as 1370 W/m². For 36 min in shadow during a 95-min orbit, the orbit-average intensity of sunlight is 62.1 percent of this value. For a mirror reflectivity of 0.85 and obscuration of 0.1, figure 3 shows overall collection

efficiency of 0.75, collection temperature being 1100 K (1500 °F) and mirror error 1 mrad (3 arc-min) or less. In addition, thermal efficiency of the receiver itself is herein taken as 0.97. Net heat output from the mirror and receiver is then 617 W/m² of collector frontal area.

The 10-kW Brayton powerplant previously tested achieved an overall efficiency of power generation of 0.29; correspondingly, its power per unit collector area would be 179 W/m². Substitution of already-demonstrated, improved components into that 10-kW powerplant would raise this efficiency to 0.32 and its power generated per unit collector area to 197 W/m². These values are 4.3 and 4.7 times the 42 W/m² of silicon-cell photovoltaic arrays, the substantial gain sought for the space station.

This performance is all at the 10-kW level. If the desired power output of each power module were, say, 40 kW, then the performance attainable from the compressor and turbine of the powerplant should rise somewhat (fig. 9). The parasitic losses for controls, bearings, and seals should all decrease as fractions of powerplant output. The achievable efficiency for the powerplant should thus be at least as high as these demonstrated values.

Nuclear Power for Space Station

A given Brayton-cycle power-generating system can function equally well with heat supplied by either a solar mirror or a nuclear reactor, operating temperatures of the powerplant being kept constant. For that very reason, such a power-generating system could benefit from the compactness of a nuclear reactor (compared with a collector of solar energy) with minimum technological risk. This increased compactness effectively removes the space station's ceiling on power generation and would thereby greatly expand its capacity for materials processing and for scientific experiments. The very same design of reliable power generator proven in service aboard the space station could be coupled to a nuclear reactor having an outlet temperature of, say, 1100 K (1500 °F); the risks would be those from the reactor alone, operating conditions for the power generator being kept the same as for the solar-driven powerplants. Not only does this approach reduce the concomitant risks but it is also the approach of least cost for introducing nuclear power to the space station.

This approach also offers the potential for evolution of this nuclear powerplant through substitution and exploitation of existing high-temperature materials. Although these materials provide the capability of operation at a peak temperature of 1500 K (2240 °F), their initial use might be limited to, say, 1200 K (1700 °F), the 300 K (540 °F) reduction being purely margin to provide increased assurance of successful operation. Once operation both in space and in ground-based test facilities has been successfully demonstrated for this powerplant at the lower temperature, operating temperature could be progressively raised toward the limit of these materials.

Evolution of the powerplant in this way has both low risk and low cost. If, as in the previous example, the powerplant were successfully operated at 1200 K, then the operating temperature might be successively increased to 1300, 1400, and finally to 1500 K. If in the ground test problems are encountered at any given temperature, the preceding temperature plateau can be accepted as the already-proven condition for powerplant operation; thus, successful operation is assured and only future, potential gains in performance are at risk. The cost is low inasmuch as new technology is not required and no new powerplant or test facility need be designed or built. The existing equipment, already having operated successfully at lower temperatures, could simply have its operating temperature raised through adjustment of the temperature's setpoint. The same powerplant in the same facility and with the same test crew could continue operation at the now higher temperature.

In its tolerance of such increases in operating temperature, the Brayton cycle has a distinct advantage over the Rankine cycle. The crucial factor is the Brayton's capability to have its gas pressure set independently of its temperature. In contrast with this, the vapor pressure in a Rankine powerplant depends directly on the working fluid's boiling temperature, in accordance with the Clausius-Clapeyron equation. A Rankine powerplant is therefore more limited in its capacity to evolve through operation at progressively higher temperatures, either a change in working fluid or a redesign, remanufacture, and redevelopment of the powerplant being required instead.

Let us now examine the data base on materials that would make practical operation at temperatures up to 1500 K. The tantalum alloy ASTAR-811C (Ta-8W-1Re-0.7Hf-0.025C), for example, has already been subjected to over 300 000 hr of creep testing at temperatures from 1140 to 1920 K (1600 to 3000 °F, ref. 12). In reference 2, the data in reference 13 for 1-percent creep were correlated on Larson-Miller plots, linear regression being used to fit straight lines to the data (fig. 14). In addition, the standard deviation of the data from the correlating line was computed in each case, and a second line parallel to the first shifted to lower stress by two standard deviations. For the 2-sigma lines, the following stresses correspond to 1-percent creep in 40 000 hr:

Temperature		Stress	
K	°F	MPa	psi
1300	1880	155	22 000
1400	2060	96	14 000
1500	2240	36	5 000
1600	2420	7	1 000

Although the 36-MPa strength is adequate for designing ducts, heat exchangers, and turbine housings in a Brayton powerplant, the turbine rotor requires higher strengths. Fortunately, the turbine rotor also operates at temperatures substantially below turbine-inlet temperature. For a representative case (fig. 15) having a turbine-inlet temperature

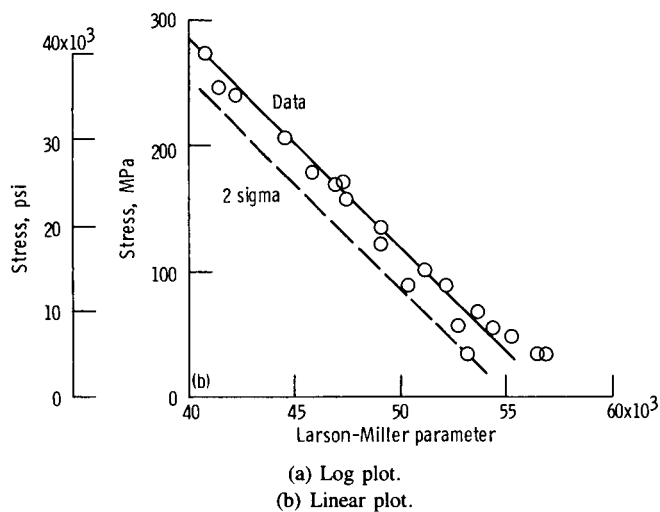
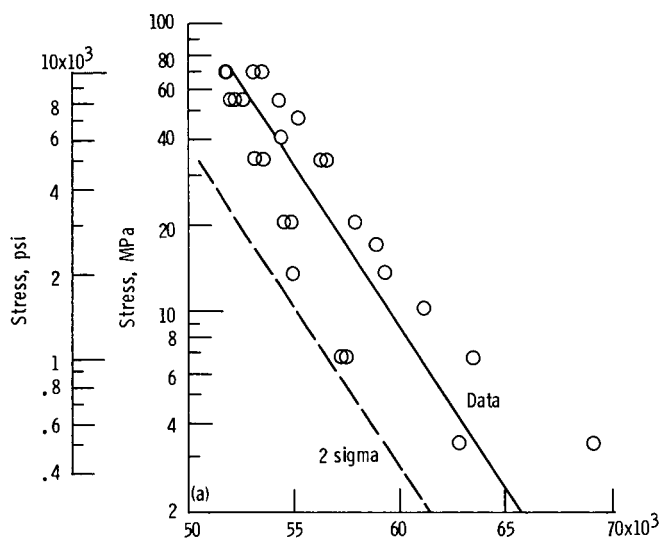


Figure 14. — One-percent creep of ASTAR-811C (Ta-8W-1Re-0.7Hf-0.025C).

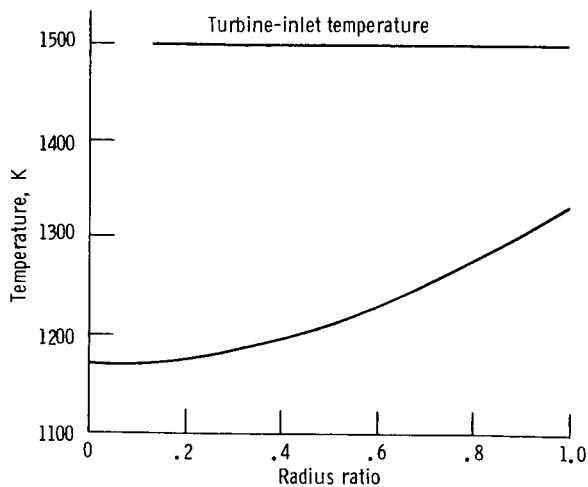


Figure 15. — Stagnation temperature on turbine rotor of Brayton powerplant.

of 1500 K, rotor temperature falls to 1250 K (1790 °F) at 70 percent of the rotor-tip radius, to 1200 K (1700 °F) at half the rotor radius, and to 1169 K (1644 °F) at the rotor centerline. For these temperatures, which are well below that at the turbine inlet, the alloy TZM (Mo-0.5Ti-0.08Zr-0.03C) is a better choice than ASTAR-811C. The creep data for TZM (ref. 13; test time, 94 140 hr) were also correlated (fig. 16). The following stresses produce 1-percent creep in 40 000 hr, an allowance of two standard deviations again being included:

Temperature		Stress	
K	°F	MPa	psi
1169	1644	293	42 000
1200	1700	240	35 000
1250	1790	155	22 000
1300	1880	69	10 000

For designing turbine rotors, TZM is sufficiently strong at the rotor-operating temperatures, and its density is also only 62 percent of that of ASTAR-811C.

Thus, a considerable body of data on materials, even when applied in a conservative way, shows that long-duration operation of Brayton powerplants at peak temperatures as high as 1500 K (2240 °F) is feasible. Early work on extending the ASTAR family of tantalum alloys showed that peak operating temperatures might be raised by 150 to 200 K (270 to 360 °F; ref. 2); further development of ASTAR-1411C and ASTAR-1611C would be required, however.

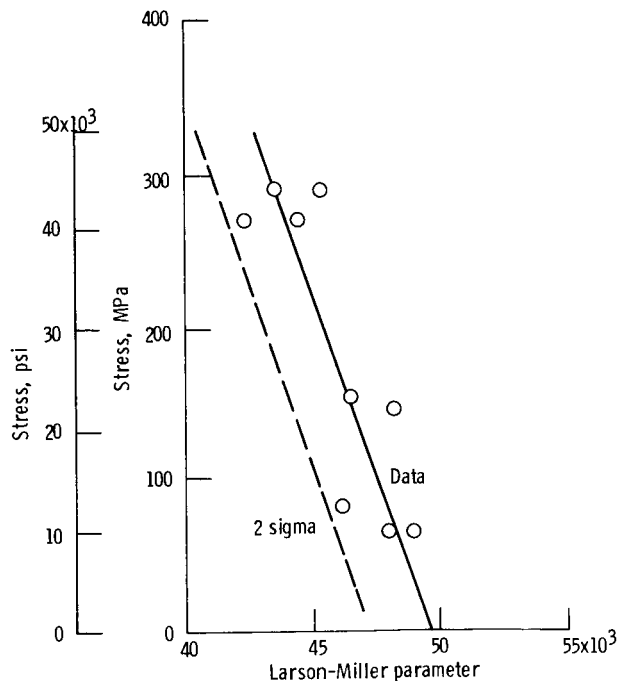


Figure 16. — One-percent creep of TZM (Mo-0.5Ti-0.08Zr-0.03C).

Very High Powers, 10 to 100 MWe

The very same technologies for generating 100 to 1000 kWe can be applied in designing nuclear powerplants to generate 10 or 100 MWe for the Strategic Defense Initiative (SDI). For these high powers, the techniques for designing turbomachinery are closer to the design practices for aircraft propulsion and stationary power than to those for generating 100 to 1000 kWe. For example, the current technology for space power systems is radial-flow turbomachinery, as appropriate to the low powers. For these very high powers, the practice would likely switch to axial flow, just as for most aircraft engines and for stationary power. The multistages that are then practical would permit changing the working fluid to pure helium, a change that would reduce the size and mass of the heat exchangers. Powerplant mass per unit power should fall accordingly.

Designing powerplants for these high powers is thus not only feasible but is actually easier than for powers of tens of kWe. Prior exploitation of the tantalum alloys at 1500 K (2240 °F) in generating hundreds of kilowatts would provide a good technology base so that powerplant development for tens of megawatts could proceed rapidly and with low risk. The corresponding reductions in the program on enabling technology as well as in the time and risk in development would likely reduce overall cost of DOD's Multi-Megawatt Program by several billion dollars.

Alternate concepts such as the potassium Rankine cycle or thermionics, if successfully developed, might achieve superior performance (ref. 2). But I question whether the resulting reduction in radiator area and powerplant mass would more than offset the lower cost and reduced risk of the Brayton cycle. The greater speed and confidence with which the Brayton powerplant could be developed would also permit the mission to begin operation at an earlier time, a factor of considerable importance in the military sphere.

The incremental, evolutionary approach could also be extended to the Multi-Megawatt Program. Early operational satellites might rely on the Brayton cycle for power generation in order to reduce the cost, time, and risk in bringing the SDI concept into actual service. Development of, say, a potassium Rankine-cycle powerplant based on the same nuclear reactor could improve later versions of the operational satellites through reducing mass and radiator area of the powerplant (ref. 2).

Summary of Results

The Brayton cycle for power generation brings together the following valuable confluence of characteristics:

(1) In an extensive technology program, the existing data base on megawatt and multimegawatt terrestrial gas turbines was extended down to 10 kW of electric power in space. At this 10-kW level, a Brayton-cycle space powerplant (complete but for its heat source) demonstrated overall powerplant

efficiency of 0.29. An endurance demonstration of this powerplant continued for 38 000 hr. Redesign and test of components of this powerplant demonstrated improved performance for the components. If these improved components were incorporated into the powerplant, its efficiency is estimated to rise to 0.32.

(2) Parabolic solar mirrors 1.5 and 6 m in diameter were assembled from sectors preformed to the parabolic shape. Optical inspection of their surface contours revealed standard errors of 1 and 3 arc-min, respectively (0.3 and 0.9 mrad). For such mirrors, theoretical analysis of heat collection estimates reradiation from the receiver's orifice to be only 2 percent of the incident heat, receiver cavity temperature being taken as 1100 K. The reflectivity of the surface coating for these mirrors was measured to be 0.88, and its durability has been demonstrated for 44 months in space. Mirror heat-collection efficiency can thus be conservatively estimated as 0.75, reflectivity being taken as 0.85 and obstruction of sunlight as 0.10. The techniques for assembling such mirrors in space have not yet been evolved.

(3) A solar heat receiver was designed and built of Nb-1Zr because of its predicted tolerance of the thermal cycling expected in low orbit about the Earth. LiF was selected for heat storage because of its high heat of fusion and its melting temperature of 1121 K (1558 °F). Chemical compatibility of the LiF with three Nb alloys (Nb-1Zr among them) was demonstrated for 5000 hr of simulated Earth-orbit thermal cycling between 1090 and 1310 K (1500 to 1900 °F). Three tubes of the receiver were performance tested for 2002 hr (1251 simulated Earth orbits); the measured hotspot on the Nb-1Zr was 1183 K (1670 °F), well below the maximum temperature investigated in the chemical-compatibility test. The mirror and receiver have not been tested in combination.

(4) In combination with such a mirror and heat receiver, the 0.29 powerplant efficiency demonstrated thus corresponds to 179 W of electric power per square meter of solar-collector frontal area. Substitution of improved, tested components into the powerplant would raise this power density to 197 W/m², these two power densities being 4.3 and 4.7 times that of silicon-cell photovoltaic arrays. Accordingly, the concomitant reduction in atmospheric drag of the space station could decrease the risks in orbit maintenance of the station and in shuttle operations.

(5) The Brayton power-generating system is equally suitable for operation with a nuclear reactor. Aboard the space station, the reactor's compactness and independence of sunlight would increase the value of the station as a platform for observing both the Earth and space and expand its capacity for both materials processing and scientific experiments. If peak cycle temperature were held to the value already in use with a solar powerplant, development risk would be confined to the nuclear reactor, a factor not only reducing the cost and time to develop such a powerplant but also increasing the likelihood that nuclear power will be accepted by the managers of the space station.

(6) Currently available technology on high-temperature tantalum alloys shows that reactor-heated Brayton-cycle powerplants have the potential to operate at peak temperatures of 1500 K (2240 °F). Substituting these alloys into a Brayton powerplant already fully developed would reduce the risk in development of such a high-temperature powerplant. For lowest risk, such a powerplant exploiting tantalum alloys might initially be operated at a peak temperature of, say, 1200 K (1700 °F), the 300 K reduction being margin. Following a period of successful operation at that temperature in an Earth-based facility, the powerplant could be operated at successively higher temperatures until its full potential is realized, a programmatic approach also reducing risk.

(7) This technology for Brayton-cycle space power systems could then be readily extended to generate 10 to 100 MW for military applications in space by exploiting existing technology for terrestrial gas turbines in the fields of both aircraft propulsion and stationary power generation. This evolutionary approach would not only reduce risk and accelerate the date at which these high powers might actually be used in space, but it would also reduce program cost by several billion dollars.

Both the high power required and the limitations on solar-collector area for the space station give new importance to solar-energy dynamic power generation over the conventional photovoltaic concepts. Fortunately, a great deal of technology on solar-energy Brayton-cycle powerplants is available for generating these high powers and for reducing the area for solar collection to less than one-fourth that of a conventional photovoltaic powerplant.

The conditions aboard the space station provide a great opportunity for both the initial use and the gradual evolution of such advanced solar-energy dynamic powerplants with very low risk. For example, inasmuch as the powerplant is modular, failure of a single power module would result in only a partial loss of power. Also, repetitive shuttle visits to the space station will permit replacement of any failed power module as well as exploitation of new power modules of improved, gradually evolving performance.

This gradual, low-risk evolution of powerplants in service aboard the space station appears to permit successive use of the following concepts for power generation, all based on the closed Brayton cycle for power generation: power generation from a solar heat source; substitution of heat from a nuclear reactor, peak cycle temperature being unchanged; and gradually raising peak cycle temperature to the 1500 K

(2240 °F) potential of the highly investigated tantalum alloy ASTAR-811C. Further development of the family of ASTAR alloys might extend the peak cycle temperature to about 1650 K (2500 °F).

The combination of this technology for reactor-heated Brayton-cycle space-power generation with the technology for power generation via gas turbines here on Earth is also directly applicable to generating tens to hundreds of megawatts of power in space for military applications. Although those Brayton-cycle nuclear powerplants would have radiators larger than those of some alternate concepts, direct application of the precursor Brayton technology would permit use of these large nuclear powerplants much sooner and with a saving of a few billion dollars in R&D costs.

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1. Report No. NASA TP-2558		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Technology for Brayton-Cycle Space Powerplants Using Solar and Nuclear Energy				5. Report Date February 1986	
				6. Performing Organization Code	
7. Author(s) Robert E. English				8. Performing Organization Report No. E-2761	
				10. Work Unit No.	
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Paper	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract <p>Brayton-cycle gas turbines have the potential to use either solar heat or nuclear reactors for generating from tens of kilowatts to tens of megawatts of power in space, all this from a single technology for the power-generating system. Their development for solar-energy dynamic power generation for the space station could be the first step in an evolution of such powerplants for a very wide range of applications. At the low power level of only 10 kWe, a power-generating system has already demonstrated overall efficiency of 0.29 and operated 38 000 hr. Tests of improved components show that these components would raise that efficiency to 0.32, a value twice that demonstrated by any alternate concept. Because of this high efficiency, solar Brayton-cycle power generators offer the potential to increase power per unit of solar-collector area to levels exceeding four times that from photovoltaic powerplants using present technology for silicon solar cells. The technologies for solar mirrors and heat receivers are reviewed and assessed. This Brayton technology for solar powerplants is equally suitable for use with nuclear reactors. The available long-time creep data on the tantalum alloy ASTAR-811C show that such Brayton cycles can evolve to cycle peak temperatures of 1500 K (2240 °F). And this same technology can be extended to generate 10 to 100 MW in space by exploiting existing technology for terrestrial gas turbines in the fields of both aircraft propulsion and stationary power generation. Thus, this single concept for power generation has the potential to evolve in modest increments from tens of kilowatts for the space station to 100 MW for military applications in space - an approach reducing the cost, time, and risk of programs to bring this broad spectrum of powerplants into actual service.</p>					
17. Key Words (Suggested by Author(s)) Space power Solar-energy dynamic power Nuclear power			18. Distribution Statement Unclassified - unlimited STAR Category 20		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of pages 13	
				22. Price A02	